Using Our Heads to Save those of the Warfighters

NRL Studies the Helmet-Skull-Brain Response to Prevent TBI

Is today's helmet good enough?

No existing helmet protects all warfighters in all scenarios. Traumatic brain injury (TBI) accounts for a shocking 19 percent of all injuries seen in our soldiers returning from the wars in Iraq and Afghanistan. In an effort to prevent TBI, NRL is studying the dynamics of brain injury. Building on its previous successes with the GelMan surrogate model of the human torso and the QuadGard (arm and leg protection) already deployed and saving lives, the Lab's Materials Science and Technology Division, in conjunction with the Laboratory's Acoustics Division and Laboratory for Computational Physics and Fluid Dynamics, has now taken on the challenge of a system of even greater complexity: the head.

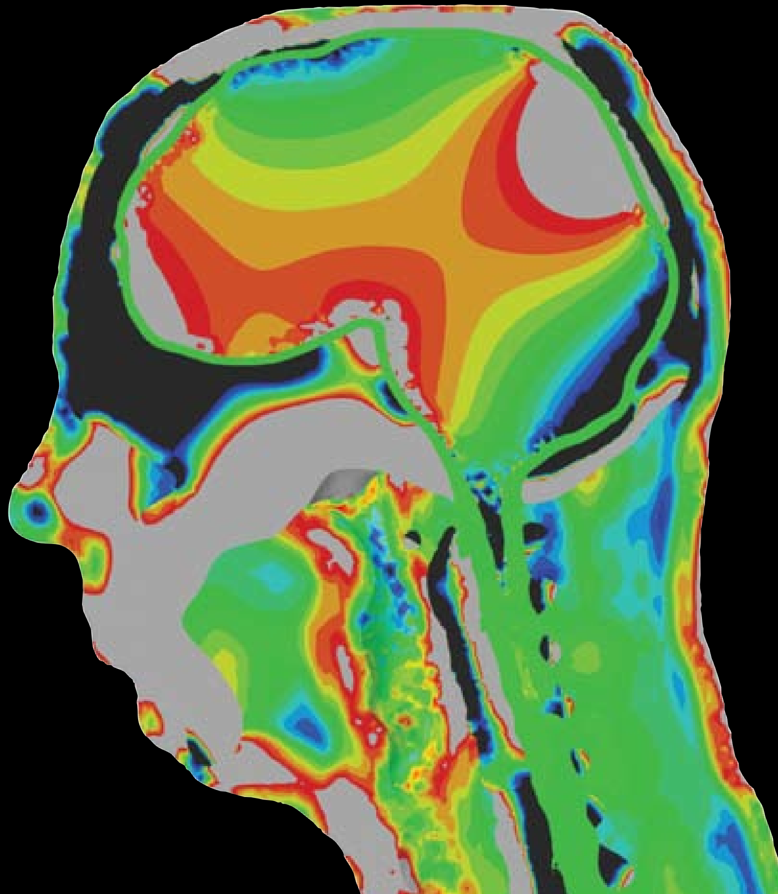
The ultimate goal of their research is to lay the foundation for designing and building a helmet that will protect the warfighter in various theaters of operation and also be mobile, lightweight, and comfortable. What is not known is precisely how the shock waves associated with blasts, ballistic impacts, and vehicular accidents affect the brain to cause mild, moderate, or severe TBI as based on medical diagnosis. Finding the answers involves modeling the response of the brain to blast and analyzing medical data from open literature to correlate biomechanical data with the dynamics of TBI.

The key is to accurately characterize the helmet-skull-brain interaction, and NRL is exploring that interaction through two parallel efforts:

- an instrumented helmet-skull-brain system, which has the capability of measuring strain and pressure to identify regions in the brain with a high potential for damage, and

- an environmental helmet sensor, which can measure and catalog real-time signatures of dynamic events during a blast or ballistic impact, relating to post-injury diagnosis.

Both of these efforts yield data on brain acceleration and consequent brain damage that bio-engineers and medical practitioners can use to interpret and better understand causes of TBI. This is just further proof that NRL researchers are using their heads to save those of others.



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Sensor Systems for Measuring Helmet-Head-Brain Response to Blast

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From World War I (WWI) to the war in Iraq, helmets have transitioned from steel to Kevlar composite materials. Just prior to WWI, helmets were non-existent because mobility and weight requirements took precedence over protection. Today mobility, weight, comfort, and protection factor into helmet design based on current threats from various ammunition, fragmentation threats, and operational environments. Inside the helmet, liners have evolved from leather to plastic suspension to sophisticated energy-absorbing padded liners, and new prototype suspensions are being tested every year to improve comfort and increase protection. Because of recent medical advances, it is apparent that experimental methods, measurement devices, and newer classes of helmets are necessary to provide warfighters with the best personal protection equipment for combating traumatic brain injuries (TBI).

TWO APPROACHES TO RESEARCHING BRAIN INJURIES

Traumatic brain injuries (TBI) are classified as mild, moderate, and severe in warfighters subjected to blasts or ballistic impacts, and in vehicular accidents. In each category, certain physical and mental impairments are associated with various parts of the brain. In open literature, most physical and visual evidence of TBI is vascular damage (detected by magnetic resonance imaging (MRI)) and brain swelling. The more subtle cases are chemical and neuronal stress that leads to cell death. As discussed in open literature, causes of TBI are not well understood by medical personnel who can only diagnose symptoms as they surface either physically or behaviorally as post-traumatic stress disorders, often months after a warfighter has returned from an assignment.

The Materials Science and Technology Division at NRL is developing research tools and measurement devices to document events that are likely to cause significant brain injuries to warfighters in battlefield environments. This paper addresses two parallel efforts for understanding shockwave interaction with the head and induced blunt force trauma to the brain. The first approach is the use of an instrumented GelMan skull-brain surrogate with an instrumented helmet. The second approach is a helmet-mounted sensor such as the newly designed NRL and Allen-Vanguard environmental helmet sensor capable of measuring and cataloging real-time signatures of warfighters subjected to dynamic events during a blast, a ballistic impact, or both. In both approaches, the data are analyzed and interpreted to measure brain acceleration to establish a fundamental understanding of brain damage. The outcome of this research can be used by bio-engineers and medical practitioners to understand and interpret causes of brain damage and TBI.

This paper has three sections. The first section describes an instrumented helmet-skull-brain system (HSB), computational results, and experimental results. The second section covers the NRL and Allen-Vanguard environmental helmet sensor system (EHS), simulation results, and experimental testing. The last section summarizes the impact of NRL's research in helmet-performance characterization.

INSTRUMENTED HELMET-SKULL-BRAIN SYSTEM

A commercial finite-element analysis tool is used to investigate the response of a head model subjected to a blast pressure from a C4 explosive charge detonated 2.44 m away from the surrogate head model. The model is comprised of a representative brain, cerebral spinal fluid, the skull with cervical vertebrae, and generalized tissue (Fig. 1(a)), and constrained at the

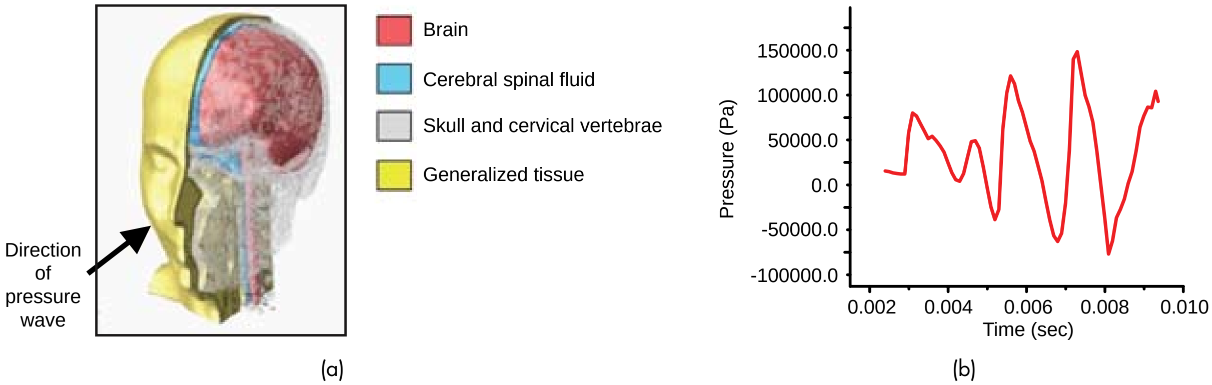


FIGURE 1
(a) Finite element mesh of head. (b) Pressure profile on the face of the head from a 0.45 kg C4 charge exploded at 2.44 m from the head.

shoulder. The blast pressure impacting the head model is shown in Fig. 1(b). The three-dimensional finite-element mesh of the head with neck and shoulders is constructed from an MRI scan of a 50th percentile male. The brain tissue and skull properties are from open literature. The brain is modeled as viscoelastic, the cerebral spinal fluid as a hyperelastic material with a low shear stress and a high bulk modulus, and the skull with cervical vertebrae and the generalized tissue are considered to be linear elastic materials.

Figure 2 shows the pressure contours in the head as a result of the applied blast pressure wave. Immediately following the blast (time = 3.30 ms and 3.77 ms), the stresses develop primarily in the stiffer modulus material, the skull. Tensile and compressive stresses in the direction of the wave propagation then begin to increase near the surface of both frontal and occipital lobes. At later times (between 4.47 ms and 5.00 ms), oscillating compressive and tensile stresses are observed that travel along the surface of the frontal lobe, the parietal lobe, the occipital lobe, and the cerebellum. As the blast pressure increases further (more than 5.00 ms), tensile and compressive stresses increase briefly at the surface of the frontal and occipital lobes of the brain in the direction of the propagating wave. After 6.17 ms, shear and longitudinal stress waves develop, with varying levels of stresses evident in all lobes. This analysis of the blast wave impacting the skull-brain system clearly shows the significant internal stress variation due to a blast wave.

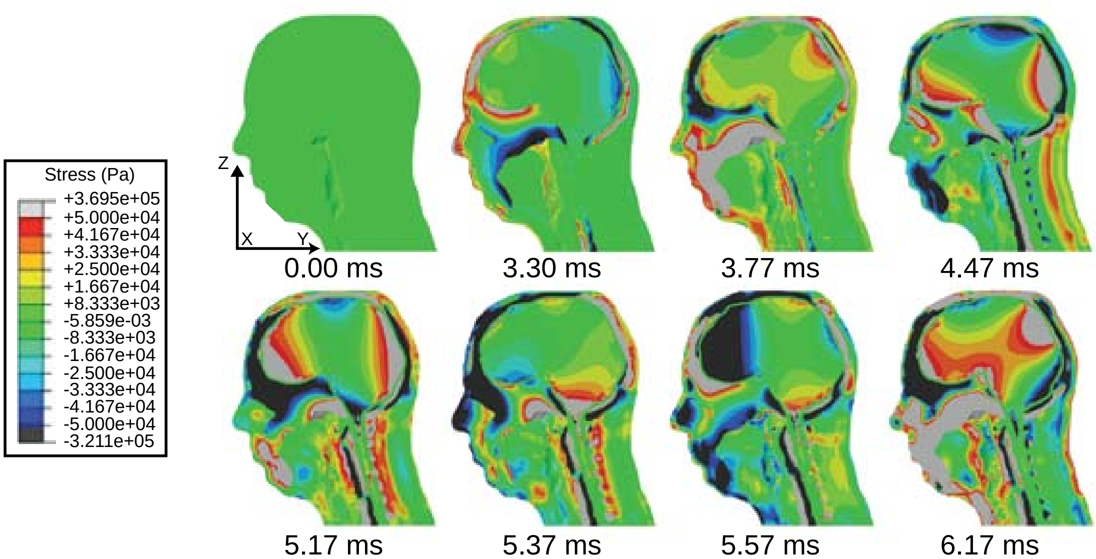


FIGURE 2
Pressure contours in the head at the sagittal plane.

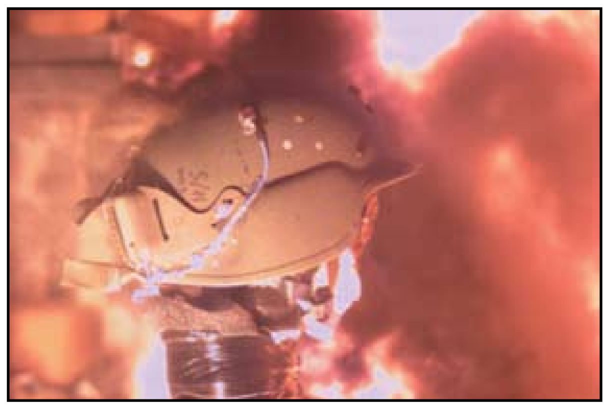
In general, the brain has a separate response in pressure from the other components (skull and generalized tissue) due to differences in wave speeds. The highest pressures observed occur primarily within the brain and mouth region. In addition, as a result of the irregular shape of the brain, there is a translational (in the Y and negative Z direction) and a rotational motion that occurs about the brain stem.

The HSB as a system consists of three basic components: instrumented helmet, skull, and brain surrogate. The main component of this system is an anatomically shaped brain of generalized tissue simulant encased in a polymer skull. The brain is fabricated by molding a transparent pliable thermoplastic polymeric material with miniature piezo-electric accelerometers and pressure sensors strategically placed in each major lobe. Two instrumented surrogate brains were fabricated, one with 11 pressure sensors and one accelerometer, and the other with 11 accelerometers and one pressure sensor, thus allowing calculation of both pressure and strain transfer functions.

The HSB is mounted on a Hybrid III neck and stand, placed in an enclosed structure, and blast-tested using C4 explosive (Fig. 3(a)). The HSB is subjected to an initial shockwave traveling at speeds greater than Mach-1 (speed of sound in air), multiple shockwave reflections, blast winds approaching hurricane wind speeds, and flames traveling at much lower speeds. From high-speed videos we are able to visualize multiple reflections of the shockwave that combine into more complex wave shapes that produce complicated brain strains further in time. Although the flames from the blast (Fig. 3(b)) engulf the HSB, the exposure time is not long enough to ignite any of the materials or contribute to the brain response.

From accelerometers located within the various brain lobes, meaningful data such as displacements are calculated from measured acceleration time histories. In order to quantify brain response in engineering terms, average strains (Fig. 4) between sensor locations are calculated (i.e., between the lobes in the brain). The strains show the relative influence of charge weight, external motion, helmet-liner system, and distance from blast. The HSB system provides a baseline for understanding possible injury mechanisms and establishing new metrics for testing new designs of helmets and helmet liners.

(a)



(b)

FIGURE 3
(a) HSB in blast chamber. (b) High-speed video frame showing the blast wave and the flame front approaching the HSB during blast testing.

ENVIRONMENTAL HELMET SENSOR

In the battlefield, one of the common threats to the head is the effect of blast pressure fronts on the face and infiltration through the gap between the skull and the helmet. These pressures are commonly believed by the medical community to be a major contributor to brain damage and traumatic brain injury. To understand the effect of such pressure infiltration, NRL conducted blast tests with an instrumented head-helmet system and complemented it with computer simulations for a better representation of the sequence of events in a blast.

Allen-Vanguard and NRL used two mannequins wearing Marine Corps lightweight helmets with current production pads and face shields, and placed them in close proximity to a blast of a commercial explosive, such as C4. The mannequins were instrumented with pressure sensors at F3 on the forehead, over the ear, and at R2 on the back of the head (see Fig. 5(a)). Computational fluid dynamic simulations were carried out for a planar shock wave approaching the helmet and head, with a gap between the head and the helmet, but no helmet liner.

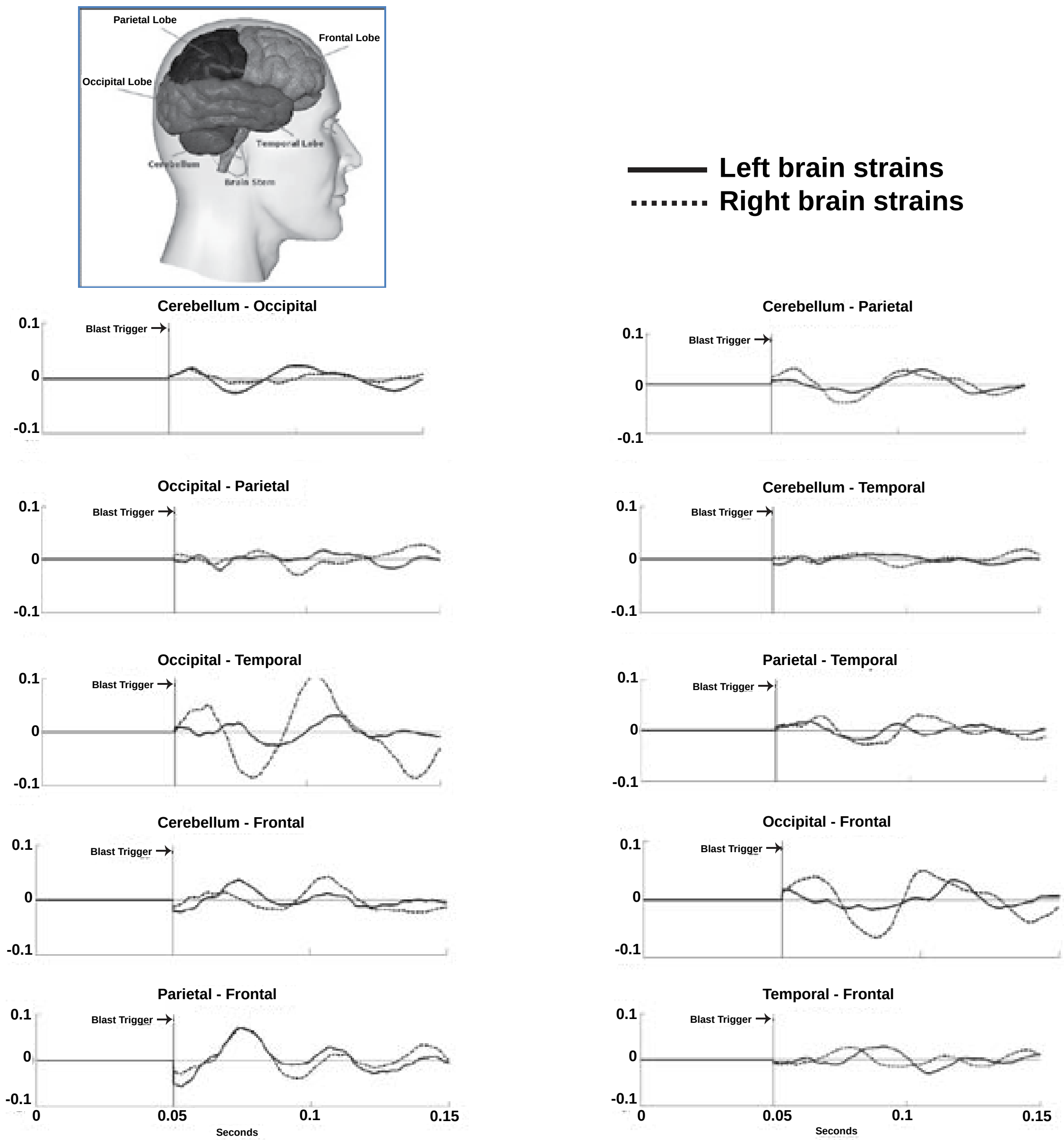


FIGURE 4
Calculated strain response from accelerometers in the brain from a C4 charge exploded at distance of 2.44 m from HSB.

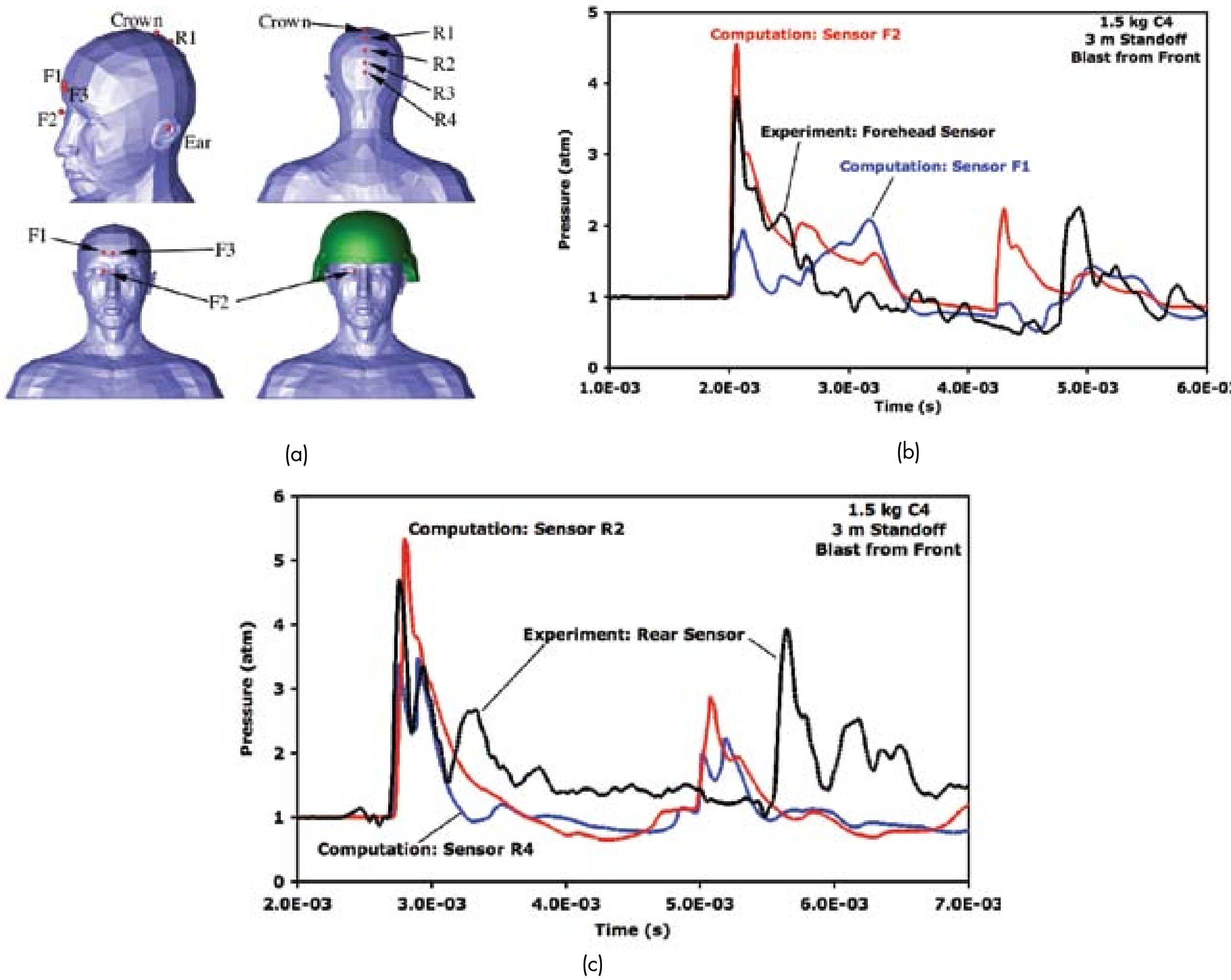


FIGURE 5
(a) Sensor locations for the computational data. (b) Forehead pressure traces for the forward blast scenario. (c) Rear pressure traces for the forward blast scenario.

Pressure histories on the front of the face are compared in Fig. 5(b). Two computational points — F1 just under the helmet and F2 just outside the helmet — are compared with the experimental data collected from the blast at F3, adjacent to F1. Computational results show that at F1 there is a considerable reduction of peak pressure compared with that at F2, exposed to the blast. Also, the experimental data at F3 seems to compare reasonably well with the computational data from F2. This suggests that there is a significant pressure infiltration between the helmet and the head.

Figure 5(c) shows the pressure histories at the back of the head, and an expanded view of the initial peaks for both experimental and computational data. Both the experimental and simulation results show a double peak at the onset followed by a third broader and shorter peak. This double peak occurs when two pressure waves, approaching from two directions, arrive at slightly different times. The computational analysis predicts a double peak formation at R4 from waves propagating around the sides of the helmet. At R2 (the experimental measurement point), the two waves traveling around the head arrive simultaneously, producing a significantly higher peak pressure at R2 than at R4. This is confirmed by computational and experimental data for R2, the point of highest pressure behind the head.

Based on these results and discussions with the Navy medical community and the Marine Corps, NRL developed an environmental helmet sensor (EHS). The EHS is designed to document the events such as blasts, impacts, and drops that occur on the battlefield. The goal is to be able to provide documented evidence for the medical community to correlate with brain damage.

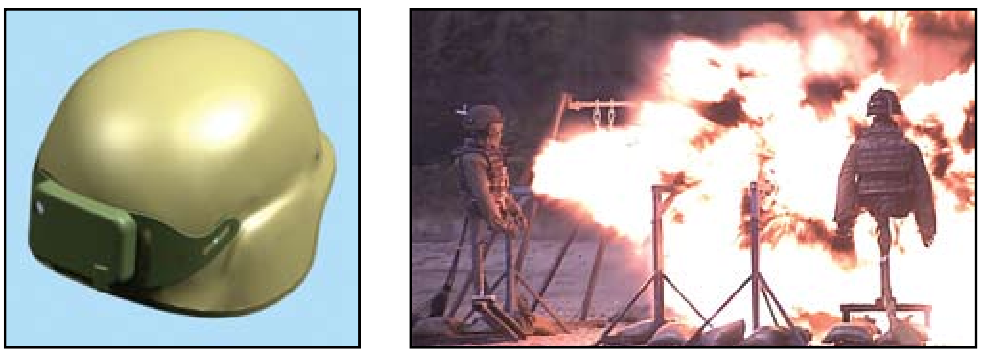
NRL developed the first prototype EHS using a three-axis accelerometer, a triggering circuit, and new control algorithms. The EHS was designed to be mounted on the back of the helmet. NRL sent the prototype to Allen-Vanguard, a major manufacturer of explosives demolition protective suits, for further enhancements. Allen-Vanguard redesigned and rug-

gedized the EHS to survive battlefield conditions, and added a pressure sensor and software to download data for 500 events. The EHS is designed to measure acceleration up to 4000 g in three directions, ambient temperature, and peak pressure up to 17 atmospheres. It also distinguishes between blast and blunt trauma events, and has batteries and electronics designed for seven months continuous operation. Figure 6(a) shows the EHS mounted on a Marine Corps lightweight helmet (LWH).

Allen-Vanguard extensively blast-tested the EHS (see Fig. 6(b)). A three-axis accelerometer was mounted inside the Hybrid III head to record head acceleration. The experimental data from blasts and other tests were used to calculate equivalent integrated head acceleration as a TBI injury criterion, similar to Head Injury Criterion used by the automotive industry to measure severity of injury in a crash. This integrated head acceleration is a first approximation to quantify brain response for blast and other threats in terms of direction of the blast and its intensity based on helmet-mounted sensors such as the EHS.

Figure 7 shows the variation of integrated head acceleration with peak acceleration for blast tests, dropped helmets, ballistic hits, and various weapon firings. Nearly all non-blast events are well below the blast data, except the data for helmets dropped on concrete, which partially overlap the lower intensity blast data. The data clearly show the ability of the EHS to make the distinction between the different types of events — blast and non-blast types — and thus provide a valuable tool to the medical community to non-intrusively collect helmet acceleration and pressure data.

Thirteen months after the inception of the program, the EHS was transitioned to a viable product by NRL and Allen-Vanguard. The U.S. Army and Marine Corps have purchased thousands of EHS units, most of which are deployed in Iraq and Afghanistan.



(a) (b)

FIGURE 6
(a) View of the helmet mounted system attached to a Marine LWH. (b) Blast testing of EHS mounted on LWH.

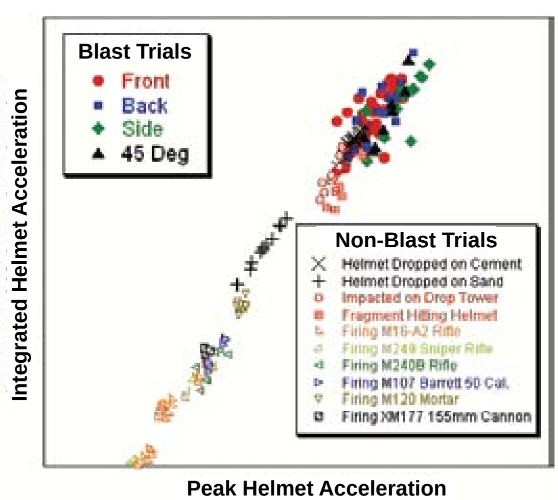


FIGURE 7
Variation of Helmet HIC with Peak Helmet Acceleration for different events in the theater.

The goal is for the correlation of data from these fielded units with cataloged injury reports to lead to validation of the helmet-mounted system while providing valuable data to help the medical community understand the cause(s) of TBI. Simultaneously, NRL and Allen-Vanguard have started development of a more compact second-generation EHS one-third of the weight of the first-generation EHS and mounted inside the helmet.

SUMMARY

This review presented two parallel efforts at NRL aimed at collecting battlefield data. The HSB is able to derive displacements and engineering strains from measured accelerations for the first time. The EHS, on the other hand, provides battlefield and other types of acceleration and pressure data non-intrusively. The combination of these data will augment the medical understanding of brain injury and provide a baseline for understanding and treating these types of injuries. The data will also be valuable in evaluating new energy mitigating materials and designs of helmet and liner systems.

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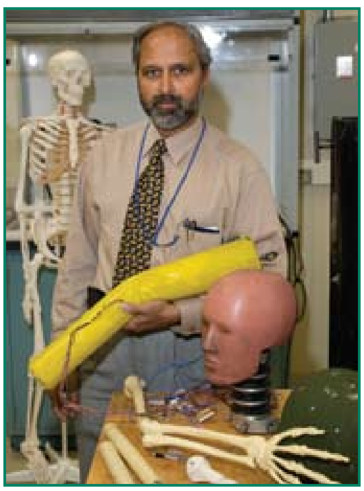
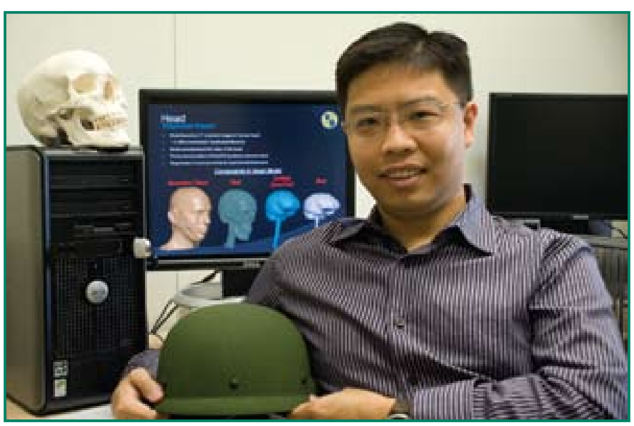


AMIT BAGCHI received a BTech (Hons) degree from the Indian Institute of Technology, Kharagpur, an MScE degree from the University of New Brunswick, Canada, and a Ph.D. from Carnegie Mellon University, all in mechanical engineering. He was a faculty member at The Ohio State University and at Clemson University, and a lead R&D staff member in the automotive industry prior to joining NIST in 2002 as a program manager in the Advanced Technology Program. He has been at NRL since 2007 as a staff scientist in the Multifunctional Materials Branch. His experience and formal training over the past 25 years includes modeling, analysis, and testing in materials processing; factory automation; application of systems and controls to process enhancement; and development of automated inspection for industrial production systems using robots. He is currently developing new materials and systems for body armor and test methods for characterizing body armor systems. He has over 35 peer-reviewed publications and two patents, has been a panel reviewer for NSF and NIST, and is a past chair of ASME's Manufacturing Engineering Division.



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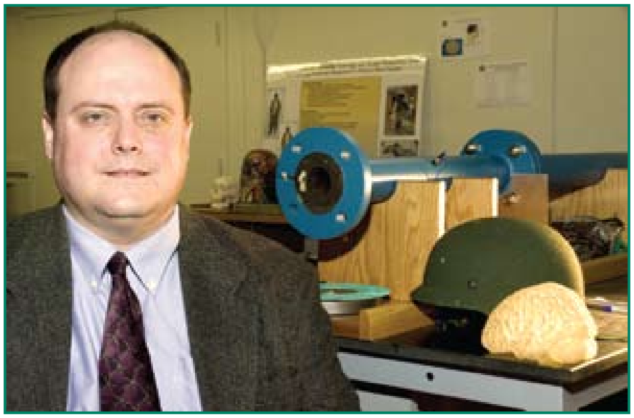

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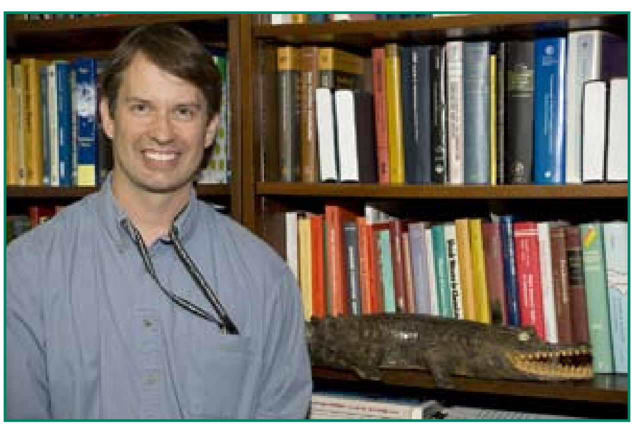

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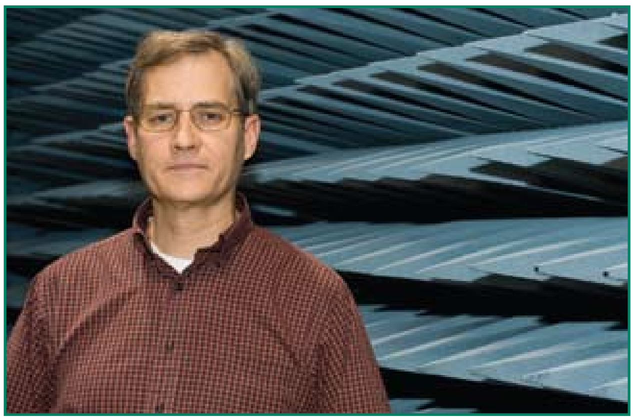

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